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TITLE: THE RF QUADRUPOLE LINAC: A NEW LOW-ENERGY ACCELERATOR

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The RF Quadrupole Linac: A New Low-Energy Accelerator*

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ABSTRACT

A new concept in low-energy particle accelerators, the radio-frequency
quadrupole (RFQ) linac, is currently being developed at the Los Alamos
National Scientific Laboratory. In this new linear accelerating structure
both the focusing and accelerating forces are produced by the rf fields.
It can accept a high-current, low-velocity dc ion beam and bunch it with a
high capture efficiency. The performance of this structure as a low-energy
linear accelerator has been verified with the successful construction of a
proton RFQ linac. This test structure has accelerated 38 mA of protons
from 100 keV to 640 keV in 1.1 meters with a capture efficiency greater
than 80%. In this paper a general description of the RFQ linac and an out-
line of the basic RFQ linac design procedure are presented in addition to
the experimental results from the test accelerator. Finally, several
applications of this new accelerator are discussed.

1. Introduction

Conventional linear accelerators, such as the magnetically focused drift-tube linac, require an input particle velocity v > 0.04 c and a rf bunching system for efficient acceleration of dc beams from an ion source. Large electrostatic injectors (>500 kV), complex rf cavity bunchers, and complicated low-energy beam transport systems are required. Recent interest in accelerating intense ion beams with linacs has generated ideas for reducing the input energy and increasing the capture efficiency. Since 1956 there have been several suggestions (Vladimirskii, 1956; Anisimov and Teplyakov, 1963; Teplyakov, 1964; Fer et al., 1963) that the accelerating electric fields could also be used for radial focusing This would eliminate the need for external magnetic focusing and also lower the injector energy requirement, because rf self-focusing is an electric force, independent of velocity.

In 1970 a particularly promising form of this idea was proposed (Kapchinskii and Teplyakov, 1970) which was based on a four-conductor configuration that produced a spatially uniform electric quadrupole focusing field. The previous proposals used specially shaped gaps or waveguides in a conventional accelerator to produce localized focusing forces. An intensive effort was initiated in 1978 in the Accelerator Technology Division of the Los Alamos National Scientific Laboratory (LASL) to develop a working model of this concept. A series of evolutionary rf cold models and the assistance of computer beam dynamics simulation codes have led to the construction and successful testing of a prototype radio-frequency quadrupole (RFQ) accelerator.

2. Description of the RFQ

In the RFQ the electric field distribution is generated by four vanes arranged symmetrically around the beam axis, as seen schematically in Fig. 1. The vanes are excited with rf power so that at any given time, adjacent vane tips have equal voltages of opposite sign. If the vane tips are at a constant radius along the beam axis, designated the z-axis, then only a transverse quadrupole field is present. This electric field is focusing in each plane during half of the rf period and defocusing during the other half, giving the structure the properties of an alternating-gradient focusing system with a strength independent of the particle velocity. To generate a longitudinal accelerating field, the vane tip radii are periodically varied, with the vane tips in one plane at a minimum radius when the vane tips in the orthogonal plane are at a maximum radius, as shown in Fig. 1. Figure 2 shows a cut through one plane of the vanes, and defines the radius parameter a, the radius modulation parameter m, and the length of a unit cell in the structure, $\beta\lambda/2$, where $\beta \equiv v/c$ and λ is the wavelength of the rf excitation. The longitudinal field is generated within this cell length between the vane tip minima in the two orthogonal planes, thus the unit cell corresponds to one acceleration gap. Adjacent unit cells have oppositely directed axial fields so that only every other cell contains a particle bunch. The electric field distribution can be obtained from the lowest order potential function and has been previously described (Kapchinskii and Teplvakov, 1970).

The shape of the hyperbola-like vane tips necessary to produce the correct electric fields is described by an equipotential surface in the electrostatic solution for the structure (Stokes et al., 1979). The correct shape is necessary to accelerate the beam with minimum loss, and this is accomplished by

fabricating these surfaces with a numerically controlled vertical mill
(Fuller, Williams and Potter, 1979).

Several configurations have been suggested for resonant cavities to drive
the four-vane RFQ (Teplyakov and Stepanov, 1968). After a series of low-power
studies on various models, the LASL effort has been to develop the RFQ as a
four-vane cavity operating in a TE210-like mode with end tuners and special
vane terminations (Potter et al., 1979), driven by a coaxial manifold having a
symmetrical, multislot coupling to this cavity. A coupled circuit model that
describes the properties of the four-vane resonant cavity and the rf power
coupling circuit has been developed (Potter, 1979). In addition, a power test
that used an unmodulated four-vane cavity determined the sparking limit of the
vane tip fields and showed that the surface fields necessary for acceleration
could be reliably obtained (Williams et al., 1979).

3. RFQ Design Procedure

The RFQ design approach at LASL has been previously described (Crandall,
Stokes and Wangler, 1979). In the most general application, it combines four
sections: the radial matching section, the shaper, the gentle buncher, and the
accelerating section. In the radial matching section the vane aperture is
tapered to adjust the focusing strength from almost zero to its full value in
a very short distance to allow the dc beam injected into the structure to be
matched into the time-dependent focusing. In the next two sections, the
shaper and the gentle buncher, the beam is adiabatically bun hed as it is
accelerated. At the end of the gentle buncher, the synchronous phase angle of
the beam reaches its final value and the bunched beam is then accelerated in

the final section. In this section, the vane radius, vane modulation and phase angle are held at constant values to obtain the maximum possible acceleration gradient.

If the ion species and the initial and final energy are given, and the frequency and intervane voltage are specified, the RFQ design is determined when the vane parameters and the synchronous phase angle are given along the z-axis. These independent functions must be determined to produce the radial focusing, capture, emittance growth, length, and other criteria specified for a particular application. For low beam currents, simple forms for these functions will work, but as the space-charge force increases more complex functions are necessary to minimize particle losses and emittance growth.

4. Experimental Results

An essential step in evaluating the RFQ as a low-energy accelerator was the design and construction of a full power test accelerator. Figure 3 is a schematic view of this accelerator, showing the RFQ cavity and power manifold arrangement. This test accelerator used an existing 425-MHz rf source, rf cavity, and 100-keV proton injector. The RFQ was optimized for the frequency, length, and input energy available. The RFQ design yielded a final energy of 640 keV for the 110.8-cm structure.

To establish the feasibility of the RFQ as a low-energy accelerator, the final energy, capture efficiency, and emittance growth were studied as a function of the input beam current and the rf field level. These measurements have shown that the RFQ performs near the levels predicted by the beam dynamics calculations. This test RFQ has operated reliably at rf fields 35% greater

than the design value, and has accelerated more than 80% of a 38-mA proton beam injected at 100 keV to a final energy of 640 keV, as verified with a 45° magnetic analyzing system. With a 15-mA injected beam the energy spread can be as small as 3% FWHM.

Figure 4 shows the results of the calculated and measured transmission for relative field strengths in the RFQ with a 37-mA beam injected into the structure. The design field corresponds to an intervane voltage of 44 kV, and a vane tip surface field of 29.6 MV/m. The measured and calculated transmission and rms emittance growth for different injected beam currents are shown in Fig. 5. The normalized rms emittance of the input beam from the 100 keV proton injector was 0.007 π cm-mrad. The difference in the experimental and calculated results can be explained as being primarily due to limitations in the transport of the low-energy (100-keV) beam from the injector to the RFQ structure. All of these experimental results are for pulsed operation, required by the power dissipation limits of the diagnostics equipment and by the available injector and rf power. However, with the necessary input power, these results apply to cw operation of the structure.

5. RFQ Applications

In addition to the proton test accelerator described above, there are several RFQ linacs now being studied or designed at LASL. These include (1) an 80-MHz RFQ to accelerate deuterons from 100 keV to 2 MeV as the initial portion of a 100-mA, 35-MeV, cw linac to be used as a neutron generator for a Fusion Materials Irradiation Test (FMIT) facility (Kemp, Liska, and Machalek, 1979), (2) a 440-MHz proton RFQ for the low-energy portion of a Pion Generator

for Medical Irradiation (PIGMI) (Knapp and Swenson, 1980), (3) a multichannel
RFQ as the low-energy portion of a heavy ion driver for inertial confinement
fusion (Swenson, 1980), (4) a general-purpose physics research RFQ for the
acceleration of all io s up to Neon, to 1 MeV/nucleon (Stokes and Wangler,
1980), (5) a 200-MHz RFQ for the acceleration of highly charged ions from an
Electron Beam Ion Source (Hamm, 1979), and (6) a 201.25-MHz RFQ for improvement
of the low-energy portion of existing proton linac facilities.

6. Conclusions

Other applications of the RFQ linac have already been suggested, so its
utilization as a low-energy accelerator for both light and heavy ions should
increase. The major advantages of the RFQ are that it will accept a low-energv
dc ion beam (50-keV protons), adiabatically bunch it with a high capture
efficiency (>90%), a accelerate it to an energy (several MeV) that is con-
venient for injection into a conventional drift-tube linac or for other
applications. These features are accomplished with minimal effects from the
space-charge force, allowing large current limits with small emittance growth.

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Fig. 1   Schematic view of the LASL four-vane structure.

Fig. 2   The RFQ vane-tip geometry.

Fig. 3.   Schematic view of the 425-MHz test accelerator.

Fig. 4.   Transmission of the RFQ as a function of rf excitation. The

points shows the measured values and the solid curve is the

prediction of the beam dynamics cal-uation for 5000 randomly

generated particles injected into the RFQ.

Fig. 5.   RMS emittance growth and transmission for various input currents.

The points give the measured values and the solid curves are the

predictions from the beam dynamics calculations.

Title

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COAXIAL TEM MODE

RFQ MODE

RF DRIVE PORT

12 COUPLING SLOTS